Chapter 11.

Out of the mouths of babes and sucklings: Breastfeeding and weaning in the past

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Introduction

Bioarchaeology by its broad definition is the study of human remains from the archaeological context. The field is particularly interested in the effects that social and environmental circumstances or change had on past human population variation. Bioarchaeologists investigate major archaeological themes such as the development of agricultural practices and subsistence change, social inequalities, industrialization, climate change and mobility through the analyses of the human skeleton (Larsen 2015). The proliferation of research over the past two decades in the bioarchaeological study of infants and children reflects a growing recognition of the importance of this life stage (Halcrow and Tayles 2008, Halcrow and Tayles 2011, Inglis and Halcrow 2017, Lewis 2007). One of the main developments in bioarchaeology is greater attention to infant weaning and child diet (Mays et al. 2017). This research is central to many archaeological and anthropological questions as it can inform us of infant feeding practices, infant and maternal health, subsistence change, food choice, childcare practices, and differential access to foods as a result of social factors. Past childhood diet and weaning processes have important implications for early and later life health, mortality patterns, physical growth, and fertility (Gowland 2015, Halcrow and Tayles 2008, Lewis 2007). Moreover, a synergistic relationship exists between diet and infection, with poor diet increasing susceptibility to infection, and infection often leading to malnutrition (Katona and Katona-Apte 2008, Lewis 2007). Human milk confers protection against infection and is a source of optimal nutrition for the neonate and developing infant (Heinig 2001, Katona and Katona-Apte 2008).

This chapter is a review of the bioarchaeology of infant and child feeding, including new sampling methods for chemical analysis, which allow re-evaluation of weaning in the archaeological past. We review paleopathological work that can contribute to our interpretation of infant feeding and weaning, including the investigation of infant mortality, developmental dental enamel defects, dental caries, dental microwear, and metabolic disease. We also evaluate interpretations of 'weaning stress' in bioarchaeological research. Finally, we illustrate how bioarchaeological lines of evidence can be combined using a case study that shows the interaction of weaning, nutritional stress, and disease in a child who died around the age of six from the Archaic hunter-gatherer period (4000BC-1700BC) in Northern Chile. This integrative case study illustrates the contribution that the investigation of breastfeeding and weaning practices can make to understanding early life histories within past biosocial environments.

Definitions of infant feeding, weaning, stress and 'weaning stress'

Here, we follow Katzenberg et al. (1996) and Millard (2000:52) in noting that "weaning is a *process* and cannot be regarded as occurring at a specific age (see also Martin, Veile and Kramer, this volume. Some studies have used the term weaning to indicate the *onset* of the process, others to indicate the *completion* of the process, and there is a tendency to try to estimate, or at least discuss, a single age of weaning." As "weaning" may be used to refer to these different parts of the process, we differentiate the introduction of non-breast milk foods (the start of weaning), the cessation of breastfeeding (the completion of weaning) and the whole period or process between these events (the *weaning process*). Clarity about terminology is essential to arriving at valid explanations of breastfeeding in the past.

In this chapter we use the term stress to refer to physiological disruption caused by environmental stressors, elicited by a number of factors including poor nutrition and infection (Klaus 2014, Selye 1950, Temple and Goodman 2014). Some bioarchaeological studies that have examined mortality patterns and physiological stress through dental enamel defects interpret their results within the context of a 'weaning stress' model, despite previous critiques based on the non-specific etiologies of these indicators (Katzenberg et al. 1996). Pearson et al. (2010), in assessing the relationship between weaning and mortality at early Neolithic sites of Anatolia, distinguish between the time of exclusive breastfeeding (EBF) and the total time of breastfeeding, on the basis that EBF is more useful for investigating impacts on fertility, morbidity, and mortality in past populations. Physiological stress and infection are more likely to occur during the start of weaning than at the end.

Chemical approaches to breastfeeding and weaning in the past

Breastfeeding, weaning, and infant diet are mainly investigated in bioarchaeology using chemical analyses of bones and teeth, and, when preservation permits, nails and hair. A proliferation of research in this area over the past decade (Beaumont et al. 2013, Beaumont et al. 2015, Dupras and Tocheri 2007, Fuller et al. 2006a, Mays et al. 2017, Tsutaya and Yoneda 2015) has resulted in the development of methods which permit chemical reconstruction of individual life histories and weaning (Beaumont and Montgomery 2015, 2016). Chemical techniques can be used as a proxy for infant feeding because dietary constituents fundamentally dictate the composition of the body's tissues (Schwarcz and Schoeninger 1991). Breastfeeding is particularly notable as it involves consumption of maternal protein by the infant or child. This, in effect, places them above the mother in the food chain, resulting in changes to their tissue chemistry relative to their mothers (Richards et al. 2002, Schoeninger and DeNiro 1984).

Several isotopic systems may be used as chemical proxies for weaning, with nitrogen and carbon isotopic ratios from collagen the most commonly employed. Isotopes are forms of the same element that have different weights, and therefore react differently to physiological and metabolic processes. Some processes will concentrate the heavier isotope, while others will preferentially incorporate the lighter one. Nitrogen isotopic ratios (given as $\delta^{15}N$ and measured in part per thousand (‰) deviation from a standard) are particularly useful for the study of weaning as breastfeeding is associated with an increase of 2-3‰ in infant $\delta^{15}N$ values relative to maternal values (Fuller et al. 2006b). Carbon isotopic values (given as $\delta^{13}C$) also shift during weaning, though the increase is smaller, around 1‰ (Fuller et al. 2006b). Theoretically, an infant is expected to show values similar to the mother at birth, a rapid increase in isotopic values during EBF, and then a return to adult values as they are weaned onto adult foods (Figure 1). There is also potential for using carbon and nitrogen isotopic ratios to identify supplementary foods used during weaning, as $\delta^{15}N$ relates to the protein component of diet and $\delta^{13}C$ to whole diet, but biased towards protein (Fernandes, Nadeau, and Grootes 2012). Supplementary feeding using animal milks (Dupras and Tocheri 2007) and maize gruels (Katzenberg et al. 1993) have been identified isotopically in archaeological samples.

<FIGURE 1 HERE>

Traditionally isotopic analysis has been used by bioarchaeologists to study infant feeding and weaning practices on a population level. In brief, this involves the cross-sectional sampling of infants and children and comparing the change in isotopic values in bones between different ages, with adult values used as a proxy for a weaned diet (Fuller et al. 2006b). As this technique has developed, increasingly sophisticated mathematical models have evolved to account for isotopic variation caused by differences in metabolism during different phases of life (Millard 2000, Schurr 1998, Tsutaya and Yoneda 2013). This cross-sectional approach has several limitations, the most significant of which is potential mortality bias since individuals sampled are, by necessity, those who died young. This mortality bias poses challenges for all archaeological studies (DeWitte and Stojanowski 2015, Wood et al. 1992), but is particularly troublesome when considering infant feeding practices and pathology. Another limitation is the uncertainty over speed of bone deposition and turnover in infants and children. These individuals are growing rapidly and collagen deposition is likely to occur quickly, but the time from cessation of breastfeeding to its reflection in bone collagen isotopic ratios is currently unknown (Prowse et al. 2008, Richards et al. 2002).

Recent methodological advances have facilitated isotopic analysis through the incremental sampling of tissues, such as hair, fingernails or teeth, which grow at known rates and do not remodel through life (e.g. Nanci 2007, Williams and Katzenberg 2012). In these studies, increments can be directly related to certain periods in an individuals' life, creating an isotopic profile that shows dietary change over time. In particular, the incremental analysis of dentine from teeth is becoming more common, allowing the high-resolution temporal comparison of $\delta^{13}C$ and $\delta^{15}N$ values from the gestational period through to childhood

(Beaumont et al. 2013, Beaumont and Montgomery 2015, Henderson et al. 2014, Sandberg et al. 2014).

As these incremental isotopic techniques are applied to archaeological samples, it is becoming increasingly apparent that isotopic ratios during early life may relate not only to infant diet but also to physiological stress, which can derive from infant feeding practices and/or infection (Beaumont and Montgomery 2015). Physiological stress often involves the breakdown of the body's own tissues to meet the energy requirements of the individual (catabolism), and this process can cause further isotopic fractionation, raising tissue $\delta^{15}N$ values (Fuller et al. 2005, Mekota et al. 2006, Neuberger et al. 2013, Reitsema 2013), and either raising or decreasing $\delta^{13}C$ values (Neuberger et al. 2013). Prior to the advent of incremental techniques, it was difficult to establish whether high isotopic values in bone samples were symptomatic of stress, or merely represented continued breastfeeding. Now isotopic profiles showing changes from the last few months *in utero* to the end of tooth formation at several years of age can help tease apart these two processes. Unusually high $\delta^{15}N$ *in utero*, for instance, may be indicative of maternal stress, while spikes in $\delta^{15}N$ which are not echoed in $\delta^{13}C$ could be evidence for acute stress (Beaumont and Montgomery 2016, Beaumont et al. 2015). It may therefore be possible to evaluate when stress is occurring and how this may be related to the weaning process using chemical signals as well as macroscopic skeletal stress markers.

All isotopic approaches are limited by analytic uncertainties. Typically, these uncertainties are ±0.2 ‰ at 2 standard deviations, so if the isotopic shift associated with breastfeeding and weaning is 2-3‰ in $\delta^{15}N$, contributions of weaning foods or breastmilk cannot be reliably detected when they are less than 7-10% of dietary protein. If the baseline for the weaned diet is taken from adult female values, then there may be variation of ±1‰

about the mean (e.g., Fuller et al. 2006a) and contributions of breast milk less than 30-50% may not be detectable.

Bone pathology, skeletal stress markers and infant feeding

Interpretation of physiological stress in infants and children is often drawn from markers on the bones and teeth that are “non-specific” and therefore not necessarily indicative of their specific etiology or cause (Larsen 2015). These stress indicators include developmental enamel defects, indicators of an anemic response represented by a pathological lesion type in the orbits (cribra orbitalia) and cranial vault (porotic hyperostosis). Physical growth stunting offers another means of assessing stress using a comparison of long bone lengths and dental development, the latter of which is expected to be less affected by environmental stressors (Cardoso 2007). Some micronutrient deficiencies can develop in infants and children with poor weaning foods, and/or or poor maternal health, such as Vitamin C (scurvy) and Vitamin D (rickets) and may leave specific bony pathological lesions (Brickley and Ives 2008, Snoddy et al. 2016).

Oral health, dental wear and infant feeding

Bioarchaeologists are also beginning to study patterns of dental macrowear and microwear in order to assess types of weaning foods and the timing of weaning in the past (Mahoney et al. 2016, Mays 2016, Scott and Halcrow 2017). Different foods produce different patterns of microwear (Hillson 1996). In adults, molars are used in wear studies as they are used for grinding food, but in infants they erupt after incisors, so they are not as useful for assessing the early introduction of complementary foods. Mays (2016) presents a method to estimate weaning using macroscopic levels of wear in deciduous incisor teeth from the British mediaeval site of Wharram Percy and compares these patterns with the isotopic weaning data from the site. He suggests that weaning studies would benefit from microscopic analysis in addition to macrowear. The new application of dental microwear methods in deciduous teeth represents a promising sensitive indicator of weaning in the bioarchaeological context (Mahoney et al. 2016, Scott and Halcrow 2017). The enamel surface of teeth is examined microscopically to quantify either pits and scratches in two-dimensional analysis (Hillson 2005), or the complexity of the surface features, including the depth of features, in three-dimensional analysis (Scott et al. 2006). Mahoney et al.'s (2016) pioneering three-dimensional dental microwear texture analysis study of human deciduous teeth enabled assessment of both timing of weaning and the toughness and hardness of diet relative to age of the infants and children. Schmidt et al.'s (2016) study of infant weaning and diet from a Greek colonial site in Bulgaria found that evidence from isotopes, oral pathology and microwear generally corroborated the timing of the introduction of complementary foods at approximately 6 months of age as described in ancient texts.

Multi-technique study of infant feeding

Perhaps the most powerful approach for studying the weaning process is a combination of chemical and osteological evidence. Chemical techniques allow insight into when/if weaning is occurring, while paleopathological evidence may highlight the physiological effects of this process. Combining the techniques also enables evaluation of mortality bias (Inglis and Halcrow 2017). Cemetery samples by their very nature represent non-survivors, with survivorship potentially affected by weaning practices (Edmond et al. 2006, Habicht et al. 1986). Incremental isotopic techniques can overcome this bias, as those who survive to adulthood can also be sampled. Additionally, incremental sampling allows examination of part of the life history of the individual, not just an observation at the point of death. This provides a broader picture of the effects of physiological stress on the individual and the population. Together these lines of evidence result in a fuller characterization of the complexity and individual nature of the weaning process. Tracing individual life histories enables the analysis of the weaning transition as a process reflecting complex cultural beliefs and individual decision-making, often related to the health of the infant-mother pair (Kendall 2016, Lawrence and Lawrence 2010, Lewis 2007, Stuart-Macadam 1995) rather than simply a dietary shift (Adair, Popkin, and Guilkey 1993, Beaumont et al. 2015, Rempel 2004).

Combining paleopathological and isotopic techniques to study infant-feeding practices: a case study from the northern Atacama Desert

The importance of combining paleopathological and chemical lines of evidence when studying infant feeding practices in the past is illustrated here using a case study from the Archaic hunter-gatherer period (4000BC-1700BC) of the northern Atacama Desert, Chile (Figure 2). This is the first time the investigation of paleopathological data has been combined with new incremental sampling of isotopic ratios. There are few terrestrial resources in the Atacama, and the Archaic peoples of the area had a subsistence strategy heavily dependent upon marine resources (King et al. 2016). Ongoing research in the Atacama Desert has highlighted the potential negative impact of environmental stressors on infant health and mortality (e.g. Arriaza et al. 1998). Consequently, we expect infant-feeding practices in the region to be heavily influenced by both infant and maternal stress.

The individual in our case study (Morro 1 T17c4) was around six years old at time of death based on dental eruption and formation and is currently curated in the Museo San Miguel de Azapa. The site of Morro 1 is located on the northern Atacama coast, within the modern-day city of Arica, approximately 20km from the Chile-Peruvian border (Figure 2). We assessed whether Individual T17c4's remains demonstrated a link between infant feeding practices and health using both isotopic and paleopathological evidence.

<FIGURE 2 HERE>

Assessing infant health/feeding from incremental isotopic analyses

The left mandibular deciduous first molar of Morro 1 T17c4 was sampled for incremental isotopic analysis following Beaumont et al. (2015). This tooth begins forming approximately 3 months prior to birth and finishes mineralization at 3.5 years of age (AlQahtani, Hector, and Liversidge 2010), though in this instance not enough collagen was preserved from the *in utero*-forming portion to provide values relating to this time period. The isotopic profile generated for the individual is given in Figure 3.

<FIGURE 3 HERE>

After birth $\delta^{15}N$ values are around 2‰ higher than typical adult values for their phase (King et al. 2016), as is expected during exclusive breastfeeding. $\delta^{15}N$ values decrease between 0.8 and 1.4 years of age, indicating weaning is occurring, and from around 2 years of age there is no further change (within analytical uncertainty), suggesting human milk was contributing less than 10% dietary protein. However, the $\delta^{13}C$ values of the individual do not follow the expected pattern of a 1‰ decrease coinciding with the decrease in $\delta^{15}N$ values. Instead they increase before $\delta^{15}N$ decreases, remaining 1‰ above initial values until 2.5 years of age when they decrease by almost 2‰.

We propose two possible explanations for this atypical $\delta^{13}C$ increase prior to measureable weaning. Firstly, this may indicate supplementary feeding from early in life, using a resource with less negative $\delta^{13}C$ values than the mother's diet and milk, but with low protein content. As maize was unavailable at this time (Arriaza et al. 2008, Santoro et al. 2008), the only recorded more negative $\delta^{13}C$ resources in the area are the marine plants (King et al. 2016). If the maternal diet did not incorporate marine plants or relied more heavily on fish or marine mammals, it is possible that this discrepancy in diet could cause the $\delta^{13}C$ value pattern seen in this individual.

Alternatively, a 1‰ increase in carbon has been associated with catabolism of tissues in response to physiological stress (Fuller et al. 2006a). While normally this corresponds with an increase in $\delta^{15}N$, this may be masked by the lowering of $\delta^{15}N$ values associated with weaning. The return of $\delta^{13}C$ values to adult levels after 2.5 years of age could signify the removal of the stress after the weaning was complete. However, maintenance of catabolic processes for two years in a growing infant would also indicate severe malnutrition.

Assessing infant stress/feeding from macroscopic skeletal analyses

The individual is well preserved and approximately 60% complete, allowing thorough pathological recording from most skeletal elements. Most obviously they exhibit abnormal diplöe (inner table of bone in the skull) expansion of the frontal and left parietal bones of the skull, indicative of porotic hyperostosis (Figure 4). This diploic expansion is visible in cross section but has not penetrated the outer table of bone (cortex), suggesting that these lesions were in the early stages of formation at the time of death. Moreover, there is a discrete area of porosity in the left orbit of the individual, which may be the early stages of cribra orbitalia, a lesion of the orbits with similar pathogenesis to porotic hyperostosis. No other abnormal skeletal changes are visible in the remains.

Porotic hyperostosis and cribra orbitalia have both been, albeit at times controversially, associated with anemia in the paleopathology literature (Oxenham and Cavill 2010, Walker et al. 2009). Anemias are a common cause of pathological trabecular expansion in the human skeleton (Resnick 1995). While the diplöe expansion we have observed in this individual is mild, we argue that iron deficiency anemia is a likely cause. Since the outer cortex is unaffected, these lesions were likely in the early stage of formation at the time of death. However, this does not exclude the possibility of long-term periodic nutritional stress, as the formation of such lesions is dependent upon the length of deficiency and they may remodel completely in rapidly growing juveniles.

Physiological stress through infancy and childhood is also suggested by analysis of potential growth disturbances in the individual. To study the skeletal growth of T17c4, measurements of long bone lengths were taken using digital calipers, and dental radiographs were used to assess dental mineralization progress (Moorrees et al. 1963a, Moorrees et al. 1963b). Comparison of the dental age to skeletal development of this individual indicates that the individual does not differ significantly from the expected long bone lengths for the population (Figure 5). However, T17c4’s femoral size is of a 3.5-4 year old using growth standards from the US, while the dental age is of a 6 year old (Anderson, Messner, and Green 1964, Maresh 1970). This discrepancy is potentially too extreme to be from inter-population differences in growth rates.

<FIGURE 4 HERE>

Combining paleopathological and isotopic evidence to interpret infant-feeding behaviors

The results of macroscopic skeletal analyses aid in the interpretation of isotopic results. Our isotopic results could have multiple possible causative factors. If the rise in $\delta^{13}C$ values was stress-related, we might expect to see signs of this prolonged stress event in the skeleton. Instead, paleopathological evidence for early-life stress is minimal with lesions present only in the early stages of formation at around the time of death. However, the lack of skeletal pathology may be a consequence of frailty, which culminated with the individual's death before formation of these lesions. There is evidence for possible growth disruption, due to stress through malnutrition and/or infection. Additionally, given that this individual died prematurely, it is likely that this was from physiological stress and/or inherent individual frailty. Finally, the isotopic results could indicate initial weaning onto marine plant resources with the more typical adult diet (dominated by marine fish and mammals) being consumed by the end of tooth formation at 3.5 years of age. It is possible that this weaned diet, rich in marine recources, is responsible for the anemia that T17c4 experienced. In marine hunter-gatherer populations the dependence on fish often leads to a high burden from marine parasites such as *Diphyllobothrium sp.* and has been linked to the occurrence of anemia in these populations (Blom et al. 2005, Jamieson and Kuhnlein 2008).

Conclusion

Bioarchaeology provides a glimpse into the lives of people in the past. Stable isotope analysis, and the recent development of incremental sampling techniques, give researchers the ability to produce fine-grained temporal analyses of weaning over the early life course. When these new forms of isotopic data are used in conjunction with evidence for mortality and pathology, we can investigate the relationships between infant weaning, diet, and stress responses. We employed a combination of incremental isotopic analyses with pathological evidence to investigate infant weaning and stress from a child (Morro 1 T17c4) from the Archaic period of Northern Chile in the Atacama Desert. Our results are complex, and show that several different scenarios can explain the isotope patterns observed. There is, for example, potential evidence for dietary supplementation with marine plants shortly after birth, and paleopathological evidence for anemia which may be related to this marine weaning diet. Bioarcheological investigations, such as ours, play an important role in generating new inter-subfield dialogue about the embodied effects of sociocultural and biological contexts of breastfeeding practices in the past.

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Figure 1: Schematic showing expected changes to isotopic ratios during the transition from exclusive breastfeeding to the adult diet. Solid line shows changes to $\delta^{15}N$ values (left hand axis), dotted line shows changes to $\delta^{13}C$ values (right hand axis).

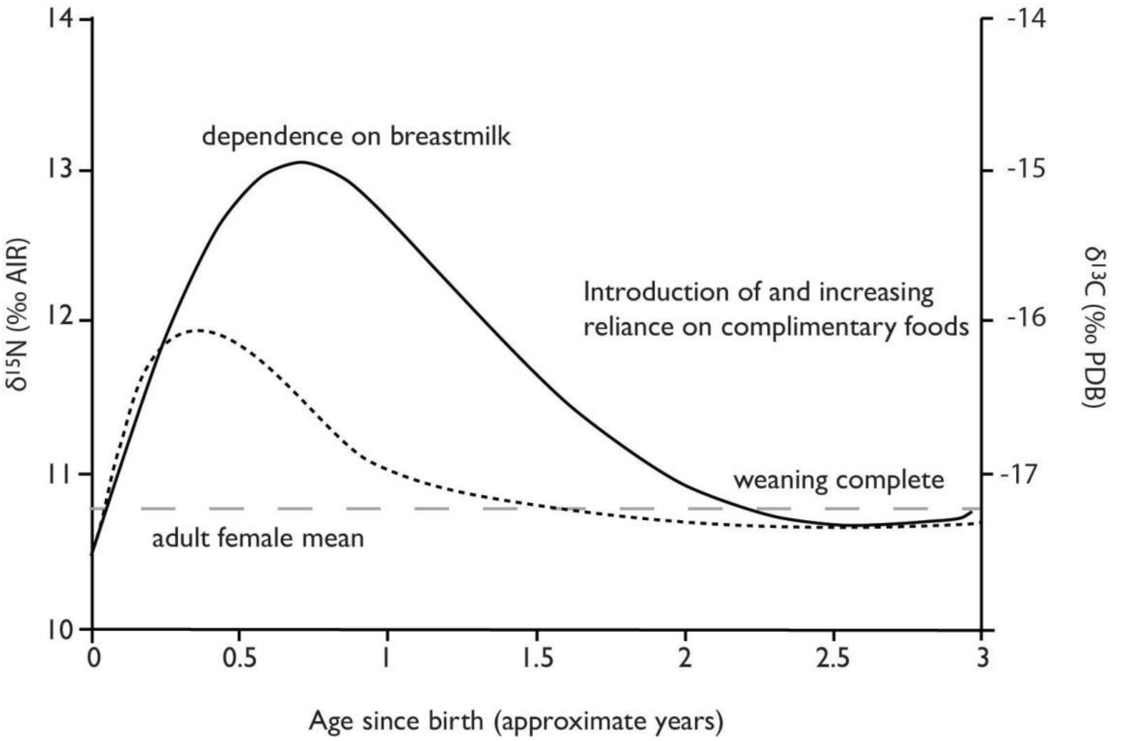


Figure 2: Giving the location of the Northern Atacama Desert, and modern day city of Arica from which individual Morro1 T17c4 derives.

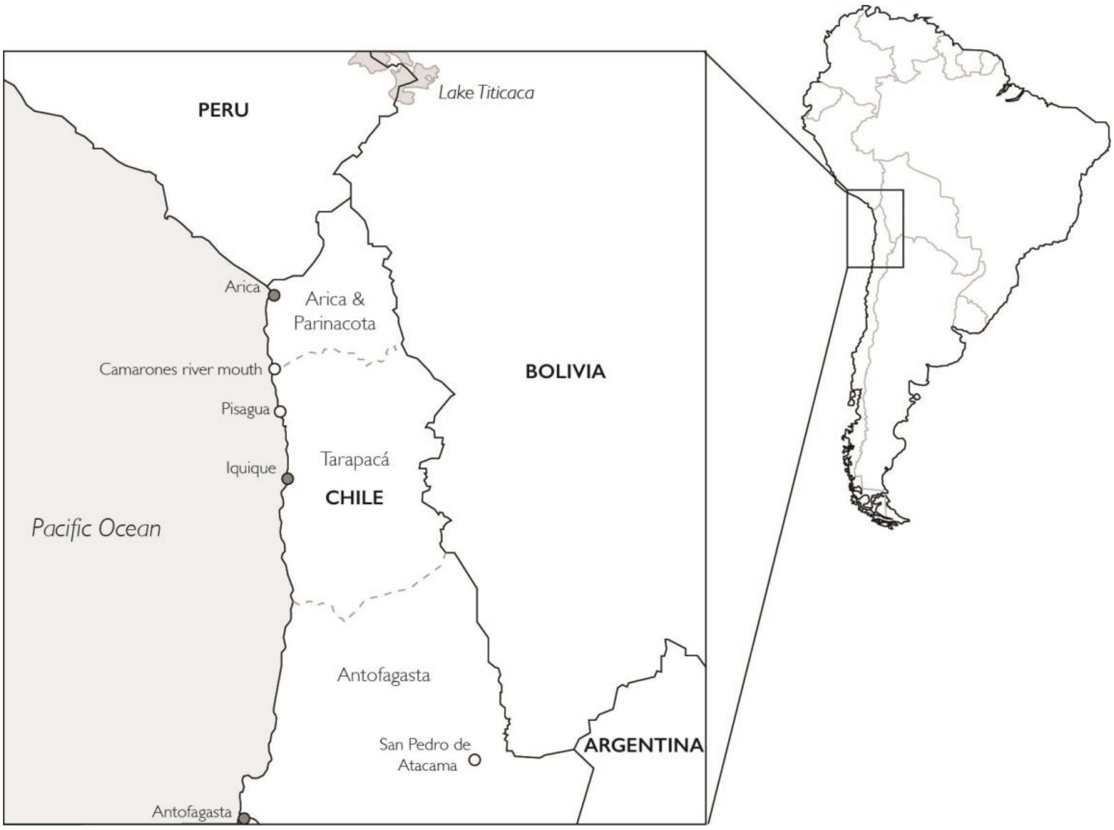


Figure 3: Isotopic profile for left deciduous 1st molar, Morro 1 T17c4. $\delta^{15}N$ values are represented by white squares on the left axis. Grey circles (and the right axis) represent $\delta^{13}C$ values.

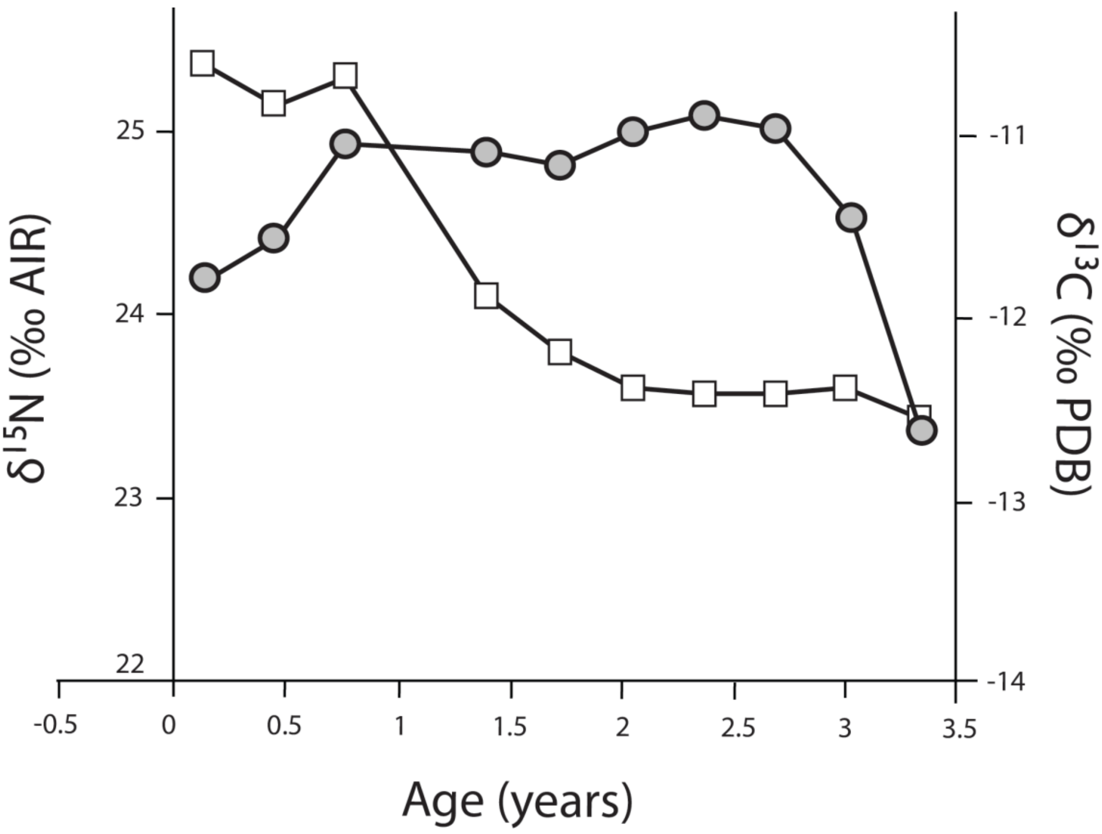
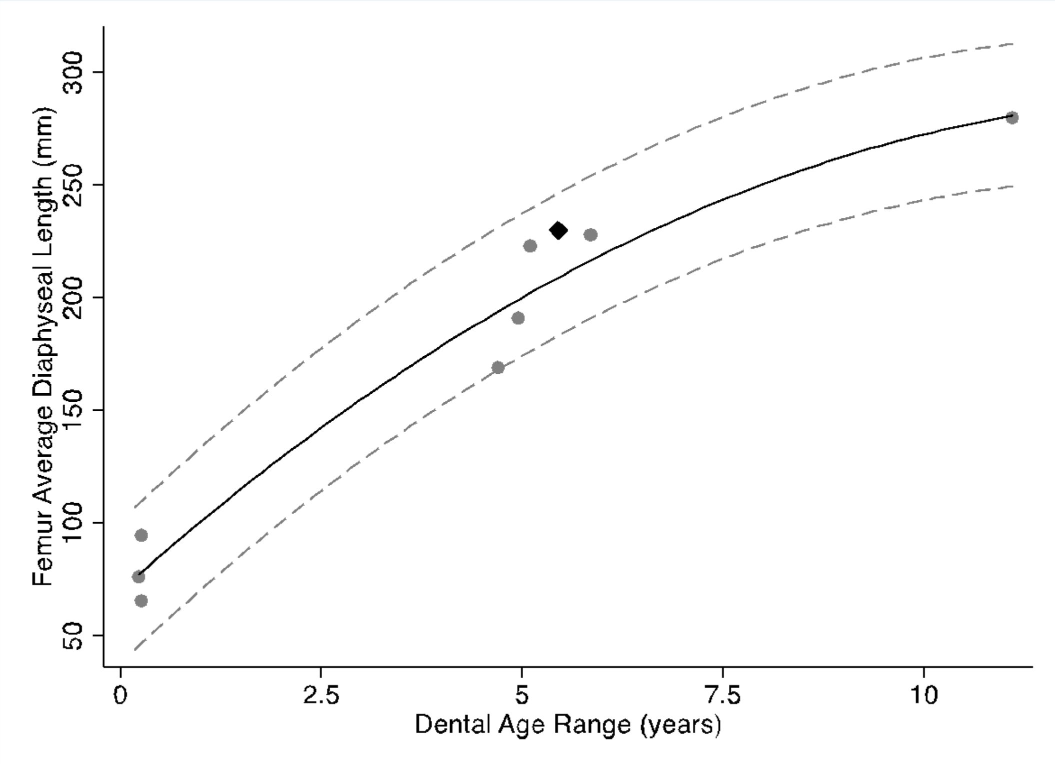


Figure 4: Long bone length vs. dental age for individuals from Morro 1. Morro 1 T17c4 is highlighted as the black diamond. The growth curve is modelled as the black line, with dotted lines indicating 2SD from the sample growth curve.



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